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Optical System Defect Propagation in ABCD Systems

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This report describes how optical system defects (tilt/jitter, decenter, and despace) propagate through an arbitrary paraxial optical system that can be described by an ABCD ray transfer matrix. A pedagogical example is given that demonstrates the effect of alignment errors on a typical optical system. Keywords:

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A general methodology for analyzing beam wave propagation in complex paraxial optical systems that can be described by an ABCD ray transfer matrix was put forth in a recent publication (Ref. 1). In the methodology is a formalism for evaluating ray tilt in a general optical system. This report is an addendum to Ref. 1 which describes how additional optical system defects may be included in the wave propagation analysis in a straightforward manner. First, the addition of ray decenters to the tilt analysis will be discussed. Second, the inclusion of despace errors will be discussed to complete the modeling of alignment defects, and lastly, a procedure for modeling the manufacturing errors of radius errors and cylinder errors will be identified.

In Section 5 of Ref. 1 tilt and jitter in optical systems were discussed and Eqs. (54)-(63) quantifying the description were presented. Equation (54) of Ref. 1 defines a Gaussian random tilt variable for the j-th optical element as

$$\underline{\theta}_j = \langle \underline{\theta}_j \rangle + \delta\underline{\theta}_j = \begin{bmatrix} 0 \\ \langle \theta_j \rangle \end{bmatrix} + \begin{bmatrix} 0 \\ \delta\theta_j \end{bmatrix}$$

If $\underline{\theta}_j$ is generalized to include a Gaussian random displacement variable, then element decenters may also be modeled using the same formalism as outlined for tilts to evaluate ray decenters. Generalizing Eq. (54) is straightforward: by including a decentor error, $\underline{h}_j$, the tilt vector, now generalized, becomes

$$\underline{\theta}_j = \begin{bmatrix} \langle \underline{h}_j \rangle \\ \langle \underline{\theta}_j \rangle \end{bmatrix} + \begin{bmatrix} \delta\underline{h}_j \\ \delta\underline{\theta}_j \end{bmatrix} \qquad (54')$$

where angular brackets denote the mean value, and the primed equations (here and below) give the corresponding modifications to the results of Ref. 1.

The changes to the remaining equations of Section 5 are straightforward. There are only four changes to the remaining equations:

$$r_j^+ = A_j^- + B_j(r_j') + h_j \tag{55'}$$

$$T_j = \begin{bmatrix} h_j \\ \theta_j \end{bmatrix} \tag{59'}$$

$$t = \sum_{j=1}^{n} [A_j h_j + B_j \theta_j] \tag{61'}$$

$$t' = \sum_{j=1}^{n} [C_j h_j + D_j \theta_j] \ , \tag{62'}$$

All other equations may be used as is to predict the performance of optical systems experiencing both ray tilts and decenters.

Another major alignment defect is despace (i.e., a change in separation between any two surface entities). This error type cannot be handled as a ray tilt or decenter. To incorporate this type of error one must include an additional translation matrix, S_j, in the appropriate location in the matrix product which describes the optical system. This inclusion will result in minor modification of Eq. (57), and Eq. (58) of Ref. 1 if necessary, to incorporate the additional matrix. Other defects may be modeled this way. Surface tilts and decenters may be incorporated directly by replacing untilted or decentered surfaces with tilted or decentered surfaces. References 2 and 3 give excellent discussions on tilts and decenters. In the same manner, the manufacturing defects of radius error and cylinder may also be included by the introduction of additional defect matrices to the system description matrix. To model radius errors, an additional powered surface is added prior to the designed surface. Cylinder is modeled by adding the defect into only one of the axes, x or y. If necessary, the cylinders may be rotated, but the resultant terms of the form "Axy" will necessitate the use of full 4 x 4 matrix analysis (Refs. 4,5). Radius and cylinder errors may also be modeled directly by a random error analysis of the curvature variables, but the inclusion of additional matrices is sometimes clerically advantageous.

A pedagogical example now follows that will demonstrate the effect of alignment errors (tilt, decenter, and despace) on a typical optical system. Referring to Fig. 1, an focal telescope is shown followed by a focusing lens. This is a typical system often encountered in practice or as a beam director to view distant objects. In this case, the model is comprised of three repetitions of the Fourier transform configuration. The first two establish an focal relay with magnification, m, and the third produces a focus for a detector. In the transform configuration, a collimated input produces a focal output and vice versa. Without defects, the model for the system is

$$\underline{y}_7 = \begin{bmatrix} 0 & f_3/m \\ -m\phi_3 & 0 \end{bmatrix} \underline{y}_1 \tag{1}$$

where $\underline{y}_1$ and $\underline{y}_7$ are the ray column vectors of the input and output planes, respectively, $m = -\phi_1 f_2$, and $\phi_j = 1/f_j$.

As indicated in Fig. 2, the defect model considered here is a despace (of separation s) between the foci of the afocal relay, a decenter h of the second afocal lens in the x-direction and a tilt θ of the focusing lens also in the x-direction. The result, including defects, is

$$\underline{y}_7 = M_3 M_2 S M_1 \underline{y}_1 + M_3 M_2 \begin{bmatrix} h \\ 0 \end{bmatrix} + M_3 \begin{bmatrix} 0 \\ \theta \end{bmatrix} \tag{2}$$

where M_i and S are the basic Fourier transform and despace ray transfer matrix, given by

$$M_i = \begin{bmatrix} 0 & f_i \\ -\phi_i & 0 \end{bmatrix}, \quad i = 1,2,3 \tag{3}$$

and

$$S = \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix}, \tag{4}$$

respectively.

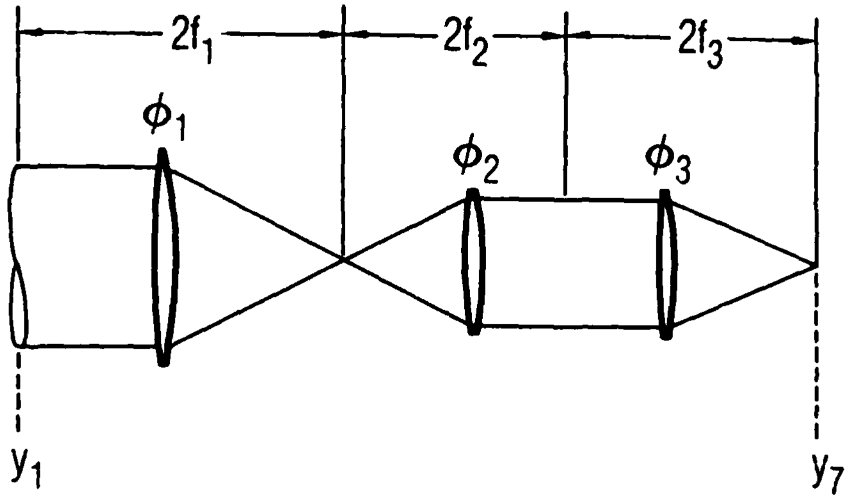

Fig. 1. The Example System Without Alignment Errors

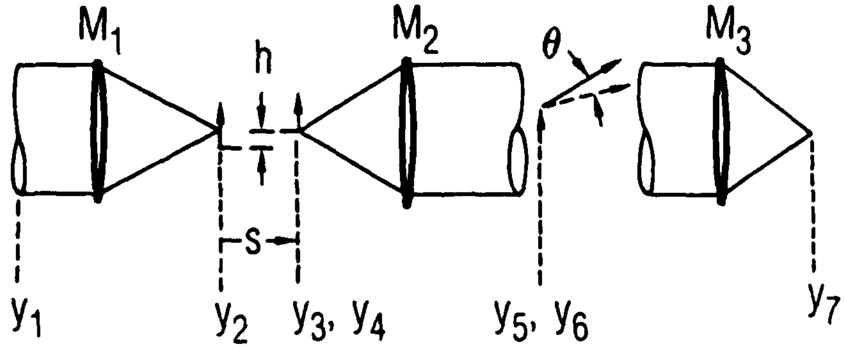

Fig. 2. The Example System with Alignment Errors: Despace, s, Decenter, h, and Ray Tilt, θ

Substitution of Eq. (6) into Eq. (63) of Ref. 1 yields the output diffracted field as

$$u(\underline{r}_2) = -\frac{ikm}{2\pi f_3} \exp\left[ik\phi_2 f_3 h\,(\hat{\underline{i}}\cdot\underline{r}_2)\right]$$

$$\times \int d^2r_1\; u_i(\underline{r}_1)\exp(-ikm\;\phi_1\phi_2 f_3 s r_1^2/2f_3)$$

$$\times \exp\left[-ikm(f_3\theta\hat{\underline{i}}+\underline{r}_2)\cdot\underline{r}_1\right], \tag{5}$$

where $\hat{\underline{i}}$ is a unit vector along the x-axis, and a constant multiplicative phase factor has been omitted. The terms outside the integral express the amplitude and a constant wavefront tilt caused by the decenter, h. The initial field, $u_i(\underline{r}_1)$, is multiplied by a quadratic phase factor indicative of the defocus caused by the afocal telescope despace. The Fourier transform term is shifted as a result of the ray tilts prior to the focusing lens. As one would expect, the alignment defects of despace, decenter, and tilt have resulted in defocus, tilt, and translation, respectively, of the output field.

A word of caution is in order regarding the modeling of alignment errors. The total ray vector with errors is given by

$$\underline{y}'+d\underline{y}' = (M+dM)\underline{y} + M(\underline{y}+d\underline{y}).$$

The first term on the right hand side, M+dM, corresponds to a system surface defect-surface tilt, decenter, or despace; while the term $\underline{y}+d\underline{y}$ represents a ray defect. When using ray tilts and decenters to model alignment errors these are not always identical to surface tilts and decenters. Consider a plane mirror. If prior to a mirror surface a <u>ray</u> is tilted, the ensuing optical system will experience a ray tilt whose magitude is equal to the additional tilt. This is because the mirror acts only as a fold in the optical path. If the mirror surface is tilted, the ensuing optical system will experience a ray tilt equal to twice the surface tilt; termed "optical

these are not always identical to surface tilts and decenters. Consider a plane mirror. If prior to a mirror surface a ray is tilted, the ensuing optical system will experience a ray tilt whose magitude is equal to the additional tilt. This is because the mirror acts only as a fold in the optical path. If the mirror surface is tilted, the ensuing optical system will experience a ray tilt equal to twice the surface tilt; termed "optical doubling". Mirrors are not the only optical elements to experience a disparity between ray defects and surface defects. Refracting surfaces also experience a difference although not as dramatic. In a refractor, if a ray tilt is used instead of a surface tilt, a weak size obliquity is not accounted for that is included when a surface tilt is used. Usually, ignoring the obliquity is of no consequence, but the fact that it is being ignored must not be overlooked.

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